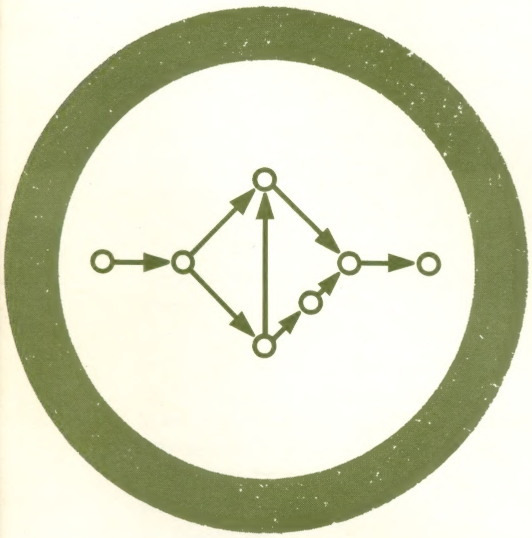
CPB-184

TAKING THE GUESSWORK OUT OF DECISION MAKING

GE 225 AND CPM FOR PRECISE PROJECT PLANNING



for project planning, scheduling and control with the GE 225

GENERAL ELECTRIC

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THE CRITICAL PATH METHOD
an optimizing time-cost planning and scheduling method

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The Critical Path Method has been programmed for the GE 225 Information Processing System. A description of the method and the GE 225 CPM program as elements of a dynamic project management cycle are presented. CPM provides a tool for *true* management by exception.

INTRODUCTION

Since the advent of the industrial revolution, it has been found increasingly convenient to define work in terms of *projects*. The acceleration of technology during the past 60 years has probably been the primary cause of such "projectizing". Pacing the expanse of technological knowledge available to business, industry, and the military, the concepts of modern business management were formulated, accepted, and applied. As the "project" (as opposed to "the continuing business") entered the business world, specific tools, consistent with established concepts, were attempted to cope with the new situation in which management found itself.

The intensively heavier demand of modern technology and of the modern competitive environment on speed and quality of performance has created the need for correspondingly more refined and accurate evaluation of project characteristics. Today, the manager of a project must be able and willing to answer questions concerning progress, changes, deliveries, costs, etc., more quickly and with greater accuracy than has ever been the case in the past. Rather than relying on the opinion and objective guidance of the man who, in the past, made more "right" decisions than "wrong" ones, the modern professional manager finds tools developed from other disciplines very effective when applied to his specific professional work elements, one of which is planning.

Likewise, the pressure and demand on the performance of the individual contributor requires that he carefully plan his work: plan his results so that they may be properly integrated with those of others and lead to achievement of over-all goals; plan his methods so that he may economically and successfully achieve the proper results; and plan his relations so that his participation becomes a multiplying, rather than an additive, factor to his environment. Consequently, careful planning is becoming increasingly important for both the manager and the individual contributor.

In recent years two basic methods have evolved which help both management and the individual contributor associated with a project. Based on the availability of high-speed, large storage capacity computing equipment, the two methods are the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT)*. CPM is a planning and scheduling tool while PERT was conceived as a project monitoring method -- an evaluation and review technique. PERT, developed by the firm of Booz - Allen and Hamilton for the Navy's Special Project Office has, however, found wide use as a planning tool.

The literature on the subject of project management has been concerned primarily with exploring structural characteristics of projects, and ranges from statements of the problem to mathematical analysis of varied sophistication. In general, it has been realized that the basic structure of a project is that all the jobs in the project must be performed in some well-defined order. Developed in parallel efforts, the two methods mentioned are the first to make explicit use of these structural characteristics. PERT has been reported in references (following this article) (1), (2), (3), and (4) and CPM case histories, and some descriptive articles may be found in references (5), (6), (7), (8), (9), (10), and (11). In the General Electric Company, much attention has been given to the PERT system since many Company components have military contracts requiring that this system be used in monitoring project efforts. A number of internal Company publications (see, for instance, references (12), (13), and (14)) are available on the PERT system while, to this author's knowledge, nothing has as yet been published within the Company on the Critical Path Method.

This paper describes the fundamental concepts of CPM and how it may be put into effect with a computer, specifically the GE 225. Some illustrative applications are described together with extensions and future possibilities.

1 A third abbreviation is also found, viz. PEP, which stands for Program Evaluation Procedure. Basically PEP is a simplified version of PERT.

HISTORY

Work leading to the Critical Path Method began in January, 1957, as an attempt to find ways to improve the efficiency of planning, scheduling, and coordinating new plant construction efforts at E. I. duPont de Nemour Company. The fundamentals of CPM were developed during the early part of that year by James E. Kelley, Jr. and Morgan R. Walker*.

Later that year some official demonstrations were given, and the new method was subsequently put to a first major test by applying it to the planning and scheduling of a $10-million project at duPont. The Critical Path effort paralleled ordinary, traditional project planning and scheduling. Comparing CPM with the results of standard procedures, it was intended to prove or disprove the feasibility of the new technique. During 1958, the method proved to be highly superior, in all respects, to the traditional planning procedures. Not only were the plans developed by the new method competitive with those developed by the traditional method in accuracy, utility, and economy but they also provided a very simple method for incorporating changes in already completed plans. In fact, it more than adequately demonstrated the ability of the method to "stay on top" of a project under implementation.

The method was subsequently used for other projects at duPont, particularly for "turn-around" project planning. During its first year in use at the Louisville plant, the application was credited with saving the duPont Company $1 million. These instances, and many others, have been reported in various papers, e.g. (15).

It is interesting to note that while PERT has been used almost exclusively on military projects, the Critical Path Method has been applied to projects where enterprise survival is based more strongly on profit making. This points to the major difference between the two methods: namely, that as a planning tool, CPM includes consideration of dollar resources while PERT does not.

Since 1958 the Critical Path Method has found extremely wide acceptance, particularly in the construction business. It has been applied by many companies with increasing success as managers and workers have developed confidence in the method and in their ability to apply it.

[2] Kelley and Walker have joined Mauchly Associates, Ambler, Penna. and Toronto, Canada, a company actively engaged in assisting various corporations in applying this technique.

In the General Electric Computer Department the method has been evaluated over the past eight months* (16), and a CPM computer program (considered faster and more versatile than any other existing program) has been written for the GE 225. As part of this evaluation, the fundamentals of CPM have been applied to marketing and manufacturing projects as well as to engineering design and development work. The basic concepts have been received with enthusiasm and have proved to be extremely valuable. With the GE 225 CPM program, it is expected that the more sophisticated features of the Critical Path Method will prove superior to existing project planning, scheduling, and control techniques.

FUNDAMENTAL CONCEPTS OF CPM

This paper aims to arouse the curiosity of those who are looking for new tools in project management - tools which will aid project personnel in planning and scheduling; in the development of balanced, optimum, time-cost schedules assuring timeliness and minimum use of resources; and which will provide a true vehicle for "management by exception". To this end, we will outline the various steps of CPM so that the reader may appreciate the concepts involved. For those who may be interested in exploring the method in greater depth, the references at the end of this paper will be of help. In addition, management consulting companies such as Mauchly Associates specialize in training personnel and in implementing the method in industrial components (26). Also, Computer Department sales engineers have received thorough training in the method and will be able to amplify the techniques and merits of the Critical Path Method with relation to the GE 225.

It is significant that both planning and scheduling are included in the title wording of this paper. Separation of these two activities is fundamental to the Critical Path Method. Planning is defined as "the act of stating what activities must occur in a project and in what order these activities must take place"; scheduling as "the act of producing project time tables in consideration of the plan and costs". As defined here, planning takes advantage of the structural characteristics of a project. The planning process is initiated by describing the precedence among project jobs, operations, or activities and is facilitated by the use of a graphic technique - the arrow diagram.

In the diagram, arrows indicate each activity in the project. The presence of an arrow depicts the *existence* of the activity and the arrow direction indicates the time *flow*. The activity arrow is a quasi-vector, the

[3] The existence of CPM was first brought to this author's attention by Mr. W. F. Williams, Senior Systems Analyst, Computer Department.

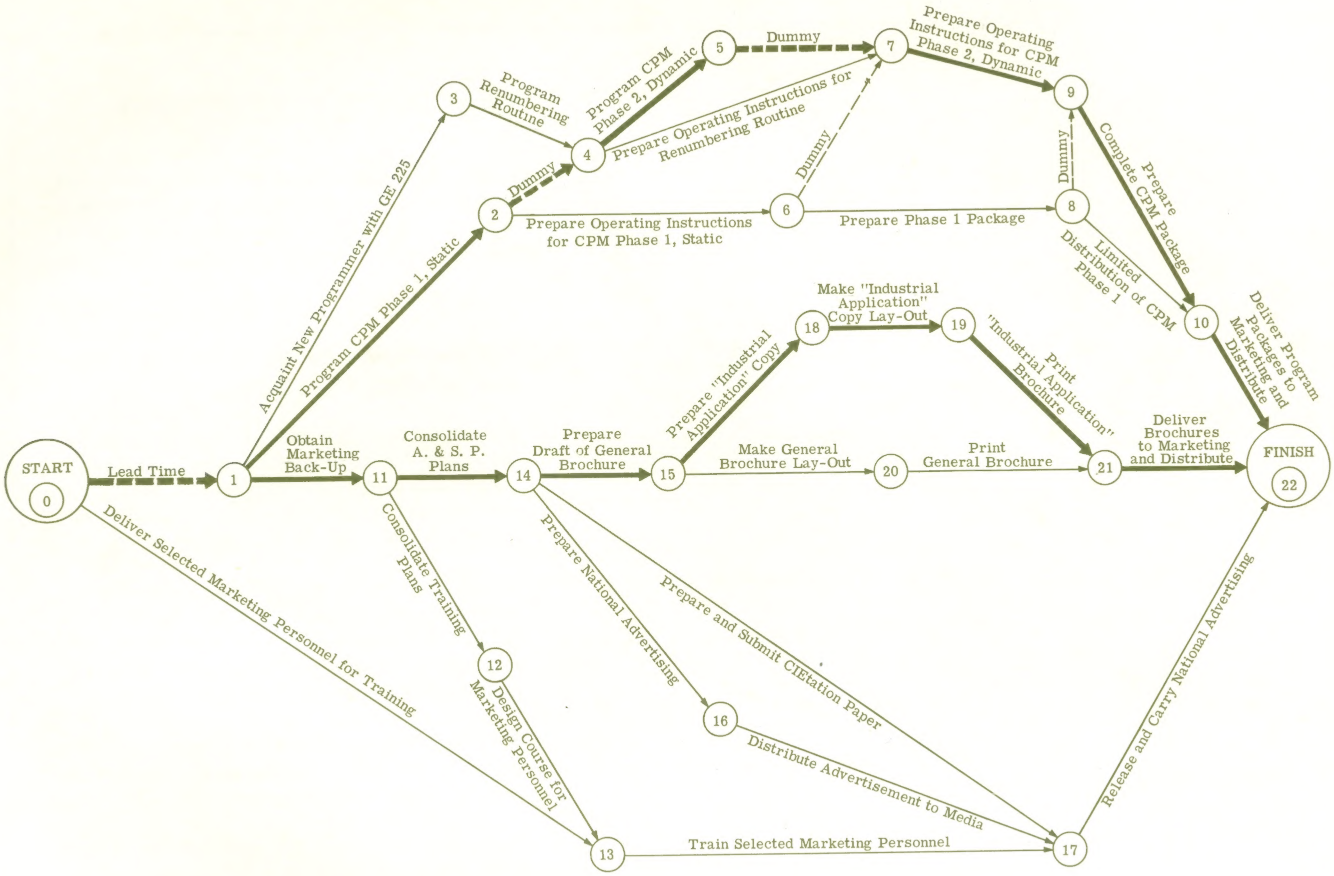
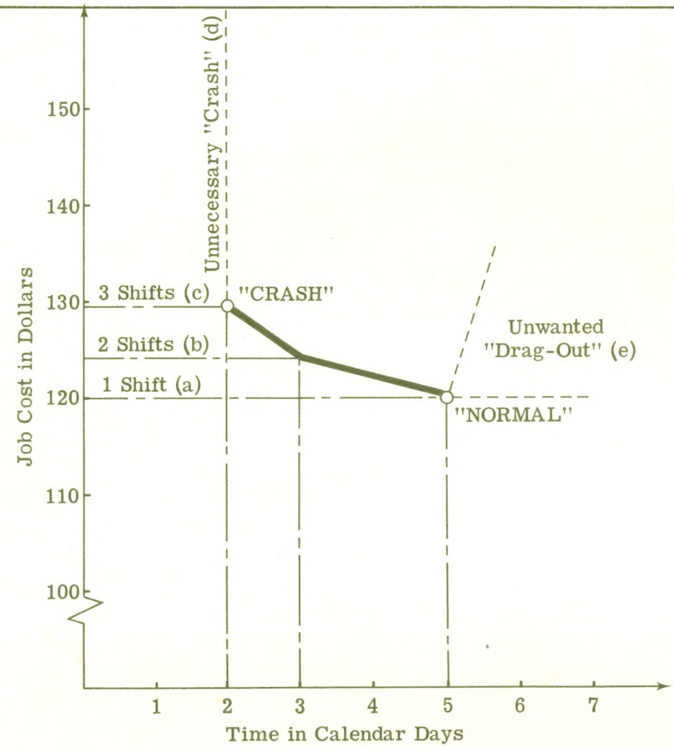


Figure 1. Arrow Diagram for launching the first GE 225 CPM program package. Times have been omitted, but critical activities are shown with heavy lines. There are two critical paths in this project.

direction in which the arrow points and the length of the arrow carries no specific significance. Only the relative position of arrows is of interest. Drawing arrows and interconnecting them in accordance with the precedence relationships between activities in the project result in an Arrow Diagram or Precedence Network which pictorially represents the project, identifies the activities that must take place, and indicates the sequence. Where a precedence relationship exists between two activities, but where no job is to be done connecting the two activities, a broken-line arrow (dummy) is used. The dummy does not require resources, neither time nor dollars.

An example of a relatively simple project arrow diagram is shown in Fig. 1. The figure represents the plan for putting a new product on the market. In this case the product is the GE 225 CPM program package and, as shown in the figure, the activities include such jobs as programming, preparation of national advertising, training of sales personnel, etc. One activity, "deliver selected marketing personnel for training", represents a so-called restraint. The inclusion of restraints is a unique feature of CPM and is a valuable tool in arrow diagramming. Other restraints may be "availability of funds", "delivery of certain hard-to-get materials", "availability of proper weather conditions", or the very important *completion restraint* used to secure scheduled completion of all or parts of the project in planning at specific instances in time. The launching of a new product is a typical application of the Critical Path Method.

Once the plan is established and the arrow diagram is agreed upon as correctly depicting the logical sequential relationships between project activities, the next step is to associate time with each of the activities of the project. In a majority of actual cases it is possible to give a single time estimate for the completion of an activity. Most activities (even a majority of those requiring creative effort) can be associated with a single time estimate. For instance, in engineering development work, previous cases of similar contents and proper partition of an activity into reasonable size elements will make it possible to estimate the activity duration.



For the "NORMAL" point, *Normal Cost* is given as the minimum job cost, and the associated minimum time is defined as *Normal Time*.

For the "CRASH" point, *Crash Time* is given as the minimum possible time, and the associated minimum cost is defined as *Crash Cost*.

Figure 2

TYPICAL ACTIVITY TIME-COST CURVE

Assume an operation the nature of which is such that only one person at a time can work on it requiring a total of 40 man-hours of work. The activity time-cost curve is then derived by consideration of possibilities such as:

(a) One man works for five 8-hour day shifts over a period of five days.

(b) Two men work on two shifts and complete the operation in three calendar days distributing the work over three day shifts and two second shifts. Because of shift premiums, the cost is higher than by (a).

(c) Three men work on three shifts and complete the job in two calendar days distributing the work over two day shifts, two second shifts, and one third shift. The cost incurred is even higher than before.

(d) *More* than three men work. The costs "skyrocket", but the calendar time can not be less than two calendar days.

(e) One man drags out the job for more than five calendar days due to incomplete instructions, communication faults, etc. Cost rises, time increases, but only 40 man-hours of work are effectively completed.

Cost can also usually be estimated with some accuracy. In fact, one may well make an estimate of the cost required to complete the activity under normal conditions as well as estimate the cost involved in completing an activity on a "crash" basis. The latter generally requires additional resources or increased facilities which may be interpreted in terms of dollars. As a result, an activity cost-time relationship can be shown graphically (Fig. 2). We normally speak of the two extreme points on this relationship as the "normal" and the "crash" points. In many cases, the relationship is well approximated by a straight line drawn between the "normal" and "crash" points. Therefore, CPM does not require that a complete curve be established -- sufficient data seldom exist. When and if the accurate data do exist, CPM considers the accurate picture including cases where the curve may be discontinuous. Consequently, a linear or piece-wise linear, continuous or discontinuous approximation to the activity time-cost relationship may be used.

Finally, two more pieces of information are always available at the planning stage of a project; namely, the earliest possible time that the over-all project can be started and the desired time that the project should be completed.

With this information in hand -- in addition to the precedence relationship as established in the arrow diagram (derived from an analysis of the activities in the project and the project objective) -- the Critical Path Method proceeds to process the information. Objective data are derived, giving alternate schedules and showing project completion in accordance with established goals, thus providing management by exception capability and timely information for managerial decisions and risk-taking. The earliest and latest starting and completion times for each activity in the project can be calculated together with the earliest time that the overall project can be completed.

Each activity in the project plays an important part. However, only a few activities -- usually approximately 10 percent -- *control* the time needed to complete the whole project. These are the so-called *critical jobs* since a delay in any one of these activities will affect all other activities following it and will thus affect the completion of the overall project. They must be started

Activity				Earliest		Latest		Floats		
i	j	Description	Duration	Start	Compl.	Start	Compl.	Total	Free	Indep.
0	1	Lead Time	0	0	0	0	0	0	0	0
0	13	Deliver Selected Marketing Personnel for Training	8.0	0	8.0	5.5	13.5	5.5	0	0
1	2	Program CPM Phase 1, Static	7.0	0	7.0	0	7.0	0	0	0
1	3	Acquaint New Programmer with GE 225	2.0	0	2.0	3.0	5.0	3.0	0	0
1	11	Obtain Marketing Back-Up	1.0	0	1.0	0	1.0	0	0	0
2	4	Dummy	0	7.0	7.0	7.0	7.0	0	0	0
2	6	Prepare Operating Instructions for CPM Phase 1, Static	.5	7.0	7.5	10.5	11.0	3.5	0	0
3	4	Program Renumbering Routine	2.0	2.0	4.0	5.0	7.0	3.0	3.0	0
4	5	Program CPM Phase 2, Dynamic	5.0	7.0	12.0	7.0	12.0	0	0	0
4	7	Prepare Operating Instructions for Renumbering Routine	.5	7.0	7.5	11.5	12.0	4.5	4.5	4.5
5	7	Dummy	0	12.0	12.0	12.0	12.0	0	0	0
6	7	Dummy	0	7.5	7.5	12.0	12.0	4.5	4.5	1.0
6	8	Prepare Phase 1 Package	2.0	7.5	9.5	11.0	13.0	3.5	0	0
7	9	Prepare Operating Instructions for CPM Phase 2, Dynamic	1.0	12.0	13.0	12.0	13.0	0	0	0
8	9	Dummy	0	9.5	9.5	13.0	13.0	3.5	3.5	0
8	10	Limited Distribution of CPM Phase 1	1.0	9.5	10.5	13.0	14.0	3.5	3.5	0
9	10	Prepare Complete CPM Package	1.0	13.0	14.0	13.0	14.0	0	0	0
10	22	Deliver Program Packages to Marketing and Distribute	2.0	14.0	16.0	14.0	16.0	0	0	0
11	12	Consolidate Training Plans	1.0	1.0	2.0	6.5	7.5	5.5	0	0
11	14	Consolidate A. & S. P. Plans	1.0	1.0	2.0	1.0	2.0	0	0	0
12	13	Design Course for Marketing Personnel	6.0	2.0	8.0	7.5	13.5	5.5	0	0
13	17	Train Selected Marketing Personnel	.5	8.0	8.5	13.5	14.0	5.5	0	0
14	15	Prepare Draft of General Brochure	5.0	2.0	7.0	2.0	7.0	0	0	0
14	16	Prepare National Advertising	3.0	2.0	5.0	9.0	12.0	7.0	0	0
14	17	Prepare and Submit CIEtation Paper	3.0	2.0	5.0	11.0	14.0	9.0	3.5	3.5
15	18	Prepare "Industrial Application" Copy	3.0	7.0	10.0	7.0	10.0	0	0	0
15	20	Make General Brochure Lay-Out	5.0	7.0	12.0	8.0	13.0	1.0	0	0
16	17	Distribute Advertisement to Media	2.0	5.0	7.0	12.0	14.0	7.0	1.5	0
17	22	Release and Carry National Advertising	2.0	8.5	10.5	14.0	16.0	5.5	5.5	0
18	19	Make "Industrial Application" Copy Lay-Out	3.0	10.0	13.0	10.0	13.0	0	0	0
19	21	Print "Industrial Application" Brochure	1.0	13.0	14.0	13.0	14.0	0	0	0
20	21	Print General Brochure	1.0	12.0	13.0	13.0	14.0	1.0	1.0	0
21	22	Deliver Brochures to Marketing and Distribute	2.0	14.0	16.0	14.0	16.0	0	0	0

Figure 3. Table of hand calculated Earliest Start and Completion, Latest Start and Completion, and Floats for activities shown in the Arrow Diagram of Fig. 1. Note, activities with no total float are critical. Latest Completion of activities (21,22) and (10,22) indicate over-all project duration: 16 weeks. Since all durations are "Normal", the table represents an all-normal schedule. Costs are not included.

and completed at given points in time unless an over-all project delay is to be incurred.

A certain amount of leeway or *float* is associated with all the non-critical activities. As can be seen intuitively, the picture can change rapidly. If float is used up in performing one activity, there may be no float available for subsequent activities. Then, non-critical activities immediately become critical.

There will be at least one contiguous path of critical activities through any project arrow diagram. This is the so-called *critical path* from which the method derives its name. Timely control of the project requires awareness of both the critical path and of the amount of leeway or float available for each activity. Both are immediately obtainable by CPM. The project manager can then devote all his skill, experience, and understanding to clearing the way for those jobs which are critical. He can anticipate troubles, bottlenecks, and possible delays and head them off *before* they become a costly reality. The critical paths through the arrow diagram in Fig. 1 have been indicated with heavy lines.

By using the concept of the Critical Path Method one may, by measuring all activity durations in consistent units (e.g., weeks), calculate a table such as shown in Fig. 3. Three different types of float have been identified: *Total Float, Free Float,* and *Independent Float* These have different significance. Total float is determined as the maximum time that can possibly be made available for the completion of an activity minus the duration of that activity. Free float is determined as the leeway available if all activities in the project are started as early as possible. Independent float is the leeway available no matter where preceding or succeeding activities are placed within their intervals of float. Independent float is always scarce, while total float is always the largest of the three. Activities with no total float are critical activities.

Fig. 3 shows that 16 weeks are required for "all-normal" completion of the over all project, the *"all-normal" project duration* (c.f. Earliest Completion, activity (21,22)). Let us now suppose that this was not satisfactory in view of competitive position. We would like to see if another schedule -- perhaps more costly -- could be arranged so that the over all project duration could be decreased to a time less than 16 weeks. Since the project duration is determined by the sum of the activity durations along the critical path, it is obvious that we must concentrate our immediate expediting efforts on those activities that have been identified as critical. Since we will attempt to keep the increase in cost as the project is expedited at a minimum, we will search for that activity along the critical path which has the lowest slope in its activity time-cost curve and which, consequently, costs the least to expedite per unit time reduction. Having decided on the least costly activity from an expediting point of view, one proceeds to prepare a new schedule incorporating the times previously estimated for the duration of each of the activities except for the one to be expedited. For the latter, a duration is chosen between the boundaries of the "normal" and the "crash" points to insure maximum expediting at minimum cost increase. Compressing one activity may result in a number of other activities turning critical. In that case, the critical path has multiplied and further compression must consider compression of activities along more than the previous critical path(s). In any event, the result will be a series of schedules, each establishing earliest and latest start and completion times as well as floats for all activities in the project, the critical path(s), and the associated direct project cost.

With the exception of the expediting, the various steps in the calculations of successive schedules can all be

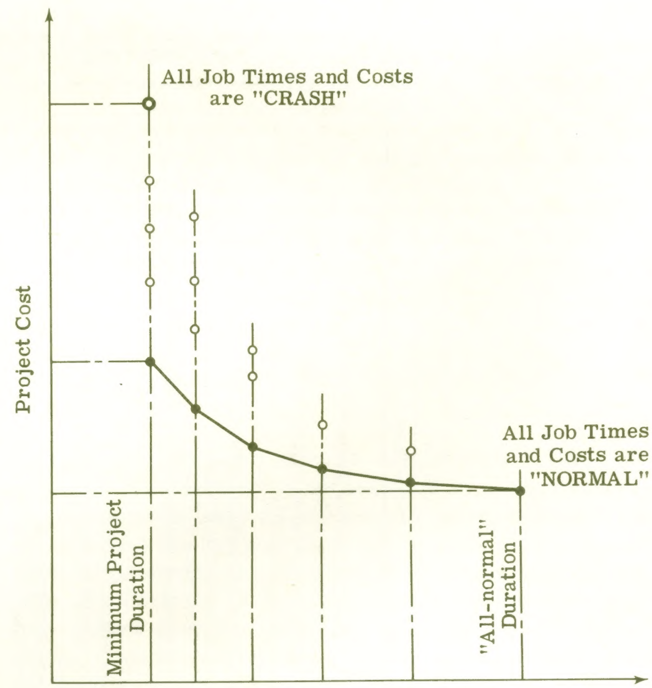


Figure 4. Typical *Direct Project Cost* curve. Between the "All-normal" and Minimum Project Durations exist (in this case) four partly expedited possible project durations. In any real project hundreds of possibilities exist for project duration and cost combinations. The mathematical procedure of CPM determines the *lowest* cost and the associated activity characteristics for each possible project duration. In the figure, the lowest costs are connected to form a piece-wise linear curve.

done conveniently by hand -- even for projects of considerable size (several hundred activities). As far as project expediting is concerned, the intuitive method indicated above cannot be effectively accomplished by hand, and even a computerized calculation based on this approach would obviously be uneconomic in terms of time and computational magnitude. However, algorithms of varying economy and sophistication have been developed in the Computer Department (18) and by Fulkerson (18), Clark (19), and Kelley (20). The resulting set of alternative schedules giving project duration and project cost (together with start and completion times and floats for all project activities) can be shown graphically as in Fig. 4. For each project duration there are many ways in which the project can be expedited. It is a definite requirement that the *least costly* way be found in each case. The curve in Fig. 4 is drawn through the (Project Duration, Project Cost) points giving least costly schedules. The other points in the diagram suggest alternative but more costly ways of attaining the indicated project durations. The desirable, optimum relationship between project duration and project cost is a piece-wise, linear, non-increasing function in the interval in which it is defined.

There are many uses for this relationship. For example, it may be desirable to *minimize* project cost, effort, or loss, or to *maximize* profit, sales, return on investment, or efficiency. Which of these criteria is selected to determine the actual schedule depends on project objectives. In industrial projects cost and return on investment are the two most commonly used criteria. The computed relationship of Fig. 4 is called the *Direct Project Cost Curve*. Clearly, there are other costs contributing to the *total* project cost such as overheads and distributives, penalties for not completing on time, etc. These additional costs must also be taken into consideration as management chooses a project implementation schedule. Usually, the overheads vary only with the duration of the project and can thus be shown as another cost curve. We may name this the *Indirect Project Cost Curve*. Adding the Direct and the Indirect Cost Curves results in a *Total Project Cost Curve*, and the schedule to be selected corresponding to a minimum total investment becomes immediately obvious. The three curves are shown in Fig. 5.

The other criterion, maximum return on investment, may be exemplified by a project which concerns the launching of a new product in time to meet a rising market; for example, placement of a new appliance on the Christmas market. The later the project is completed, the smaller will be the manufacturer's share in the market. On the other hand, the more the project completion date is moved up, that is, the further the project has been expedited, the more the project will cost. Weighing both of these factors in order to determine when production should begin gives management

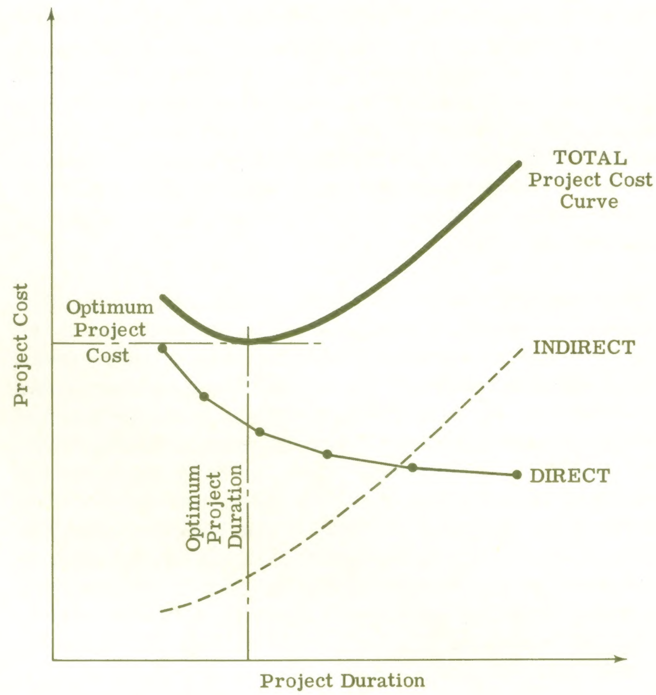


Figure 5. Typical *Total Project Cost* curve. The total project cost curve is the sum of the direct project cost curve determined by CPM and the *Indirect Project Cost* curve decided upon by the user. The optimum schedule is indicated by the minimum on the total project cost curve. The associated activity characteristics are found directly from the information produced by the GE 225 CPM program.

a so-called loss function. Adding the loss function to the total investment cost curve gives management precise data as a basis from which it is in a position to select *one* schedule from many alternatives.

The preceding remarks have, of necessity, been oversimplified, but they illustrate what happens in practice. Mathematical formulation has been avoided. The important point here is that by the Critical Path Method management is in a position to select one of many alternative schedules *prior* to implementing a project with a view to optimizing the time-cost relationship and thereby securing profit necessary to survive in a competitive market.

IMPLEMENTATION OF CPM WITH THE GE 225

The Computer Department's GE-225 CPM program performs *all* the calculations described in the preceding section. In addition, certain improvements and extensions of the concepts described are included. This section describes how the Critical Path Method can be implemented on a properly programmed computer.

Given a project to plan and schedule, a preliminary project arrow diagram is prepared. This diagram represents the initial ideas of how the project should be carried out. This is the most difficult part of the entire process. Whether this diagram is prepared by the project manager alone, by the project manager together with his supervisors and team leaders, or by a planner specifically trained in this method, is a matter of choice.

Once the diagram is complete, preliminary estimates should be made of the time cycle for each job in the project and the probable job cost. For large projects this estimate is tentative and the diagram represents a structure upon which the project manager and his team leaders can build. This diagram should be drawn in pencil on transparent paper for easy reproduction and correction. The planning team can now make its first good use of a computer. An analysis using the "all-normal" and "all-crash" routines can be made to help refine the design of the project by determining critical jobs and the project duration. It is also essential to determine the near-critical jobs and the estimated project cost.

The schedule computed at this point is called an all-normal schedule -- "all-normal" because the project activities in this schedule are considered to be completed in a usual or normal manner with available normal facilities. At this point, there are a number of possibilities for further work. The project manager may be completely satisfied with the all-normal schedule. In that case there is nothing further to be done. However, this is a rare incident. More likely the all-normal schedule will show where jobs were omitted from the diagram or where bad estimates were made. Generally, some of the data will have to be changed, new jobs will be added and old ones deleted to reflect a better overall plan for the project.

In this case, a new all-normal schedule should be computed to evaluate the effects of the changes. Such changes reflect managerial decisions and may, in many instances, be based on managerial risk-taking. The results of the second computation may again reveal where further refinements are required and indicate that a third all-normal schedule should be computed.

Up until now, only *normally available facilities* have been considered. It may still be that the overall project duration does not meet the required deadline or there may be other reasons why it will be desirable to investigate the possibility of expediting the project. Satisfied with the basic plan, management then subjects collected time and cost data to a *cost-curve computation;* that is, a computation resulting in a set of alternative schedules, each requiring additional facilities or increasing amounts of resources.

It is a large task to collect the necessary information for normal and crash durations, and for normal and crash costs for all of the several hundred jobs that comprise the usual project. Therefore, it is recommended that the cost-curve computation be made only after several revisions of the basic plan. In fact, by experience we know that an analysis of a project via an all-normal schedule will not only tell a project manager how to define the design of a project, but will also tell him to some high degree of probability what jobs will most likely be expedited in the cost-curve computation. This, in turn, will show the necessity of collecting data for the cost computation for only those jobs or activities that it seems necessary to expedite. In most cases the number is probably less than 20 percent of the total number of jobs in the project.

This constant interplay between personnel and the computer is important. It is a good example of the integrated man-computer team. Generally, it is more economical to use the computer many times for all normal computations and let it carry the major scheduling load. This means that so far as the program is concerned, it must provide quick and effective computations and it must provide for easy coordination between the planning and computer languages. The GE 225 CPM program provides all of these features.

The GE 225 computer system to process all project data for 2100 activities and 1000 arrow-diagram nodes has an 8000 word memory, four tape units, a high-speed printer, and a sorting device.

In some existing programs the activities in the input must be listed according to a certain numbering scheme. Each activity is described by a number pair, (i, j) where i is the number at the tail of an arrow and j the number at the head of that arrow, and i is less than j (see Fig. 1). In contrast, the GE 225 program accepts *randomly* numbered activities and automatically sorts and designates the activities in accordance with the (i, j) scheme. At the same time it checks for errors in the diagram.

The GE 225 program allows for priority *weighting* of each activity. Since approximately only 10 percent of the jobs in a project are critical, the remaining 90 percent will have some flexibility as to scheduled start and completion. In the GE 225 program this latitude or float may be allocated in the planning stage to specific jobs. As a result of known limitations in resources or facilities, management can, by using the Priority Weighting Factor, require the program to associate any available float with those jobs for which such limitations are most severe. This results in resource allocation consistent with priority weighting. Since all actual projects are so complex that the critical path is not

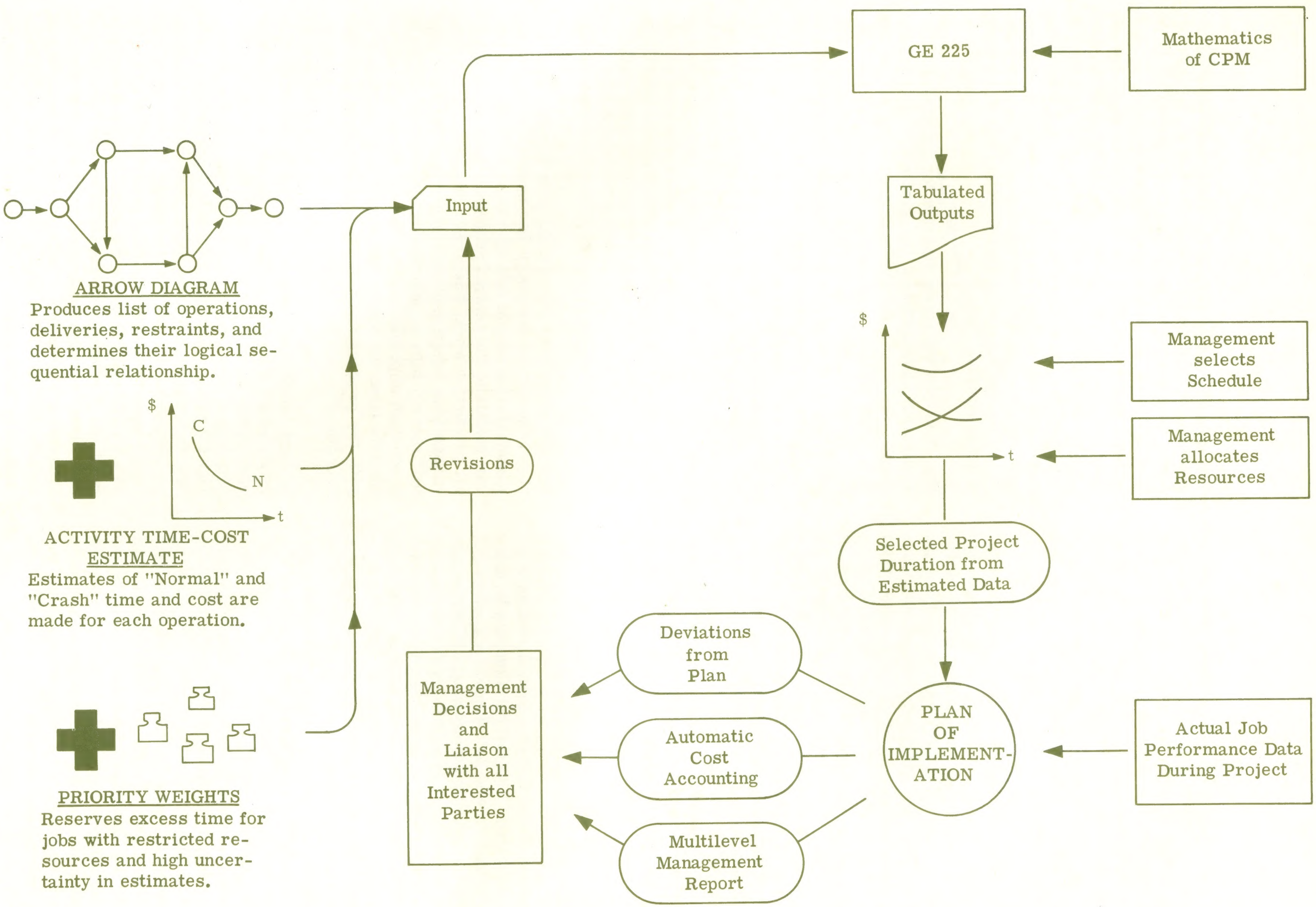


Figure 6. The dynamic CPM project planning, scheduling, and control cycle showing management by exception capability and immediate response during project implementation.

immediately evident, the GE 225 CPM program automatically allocates prime priority for critical activities and then assigns float to non-critical activities on the basis of previously-established priority weights. The resulting *Scheduled Float* and *Scheduled Completion* for each activity are included in the computer printout together with the Earliest Start, Earliest Completion, Latest Start, Latest Completion, Total and Free Floats, and Schedule Cost.

The computer program represents only a portion of the project management cycle. However, it is an important portion because it provides an effective tool for developing objective data and timely control, thus helping management to take the guesswork out of decision-making. Fig. 6 shows the complete project management cycle using the computer as a member of the team. Upon implementation, continual comparison of actual results with estimates to identify *deviations* from the plan is readily accomplished, e.g., through job accounting code numbers allowed for with the GE 225 CPM input activity description. By concentrating only on deviations from the plan, management can stay on top of a project at all times. Corrective action, when required, is not only easier to determine, but also the effects of any decisions are immediately discernible. The dynamic mechanism of the CPM cycle leads to immediate response in defining the problem and finding and implementing the best solution.

ILLUSTRATIVE APPLICATIONS

Some applications of the Critical Path Method have already been indicated. The duPont Company's early applications were followed by complete acceptance of CPM in all construction and maintenance undertakings throughout that Company. Applications and successful results have been reported from the petro-chemical industry in the United States as well as in Canada (21). Applications in the construction business have been reported by Perini Corporation (22), and Catalytic Construction Co. (23). A summary of case histories was presented by J. E. Kelley, Jr. in an invited paper before the 18th national meeting of the Operations Research Society of America (11). Kelley's case histories include applications in areas of general construction, chemical plants, buildings, bridges, power plants, etc., as well as applications in the launching of new products and manufacturing projects. The reported advantages of using the method have been time and dollar savings as well as increased insight for all concerned into the implementation of the projects and timely information for managerial decision-making and risk-taking. At A. T. & T. computer conversions are planned, scheduled, and controlled by CPM, and the Canadian Government uses the method extensively.

As was mentioned earlier, a study of the Critical Path Method has been conducted over the past eight months in the Computer Department. The GE 225 CPM program is the first result of this study. Fig. 1 shows the arrow diagram pertaining to this first phase of the CPM study. Future phases will explore extensions of the method. In the course of the study, various department components have been taught to use the method. Implementation of the CPM without the use of a computer has resulted in many advantages for the engineering, manufacturing, and marketing components. It is being used for planning the development efforts on new peripheral equipment, for budget planning, and for planning of sales efforts.

Fig. 7 shows the arrow diagram for a manufacturing application, consisting of the production cycle of the central processor for the first four units of the GE 225. Even without a computer program, at the time this arrow diagram was prepared it was possible, by relatively fast hand computations, to identify earliest and latest starts and completions as well as floats. The critical path is indicated in the diagram, and from this quite unsophisticated application of the method, a number of interesting points were brought out. For example, it was determined that the activity of moving skids with the frames for the central processor to a crane area where the heavy power supplies were lifted into place was on the critical path. By permanently installing a crane in the skid area prior to moving them, this activity could be shortened considerably and the over all production cycle expeditied correspondingly.

Another activity on the critical path was the insertion of printed circuit boards. It had been the feeling of the manufacturing people that the delivery of printed circuit boards to the central processor held up the overall production work. The arrow diagram and the hand calculations confirmed this and supported a decision to proceed with a manufacturing simulation of the production of printed circuit boards so as to integrate the flow from the production area to the insertion area with the production of central processors, and thus expedite this particular activity on the critical path.

A third conclusion from the drawing of the arrow diagram became evident as the symmetry of the diagram developed. It was observed that three very similar patterns of arrows exist in the diagram. These patterns represent the placing of modules in three cabinet racks. Before the modules are inserted, and very early in the production of the central processor, the three cabinet racks are mounted on skids (activities (1,32), (32, 33), (33, 34), (34, 35), (35, 36), and (36, 40)). From this point on, the three cabinet racks proceed as one unit and work is performed in one rack under constraints imposed by the other two. Since only the insertion of modules in one of the cabinet racks was on the critical path, it seemed logical to suggest that central processor production could be expedited by mounting the cabinet racks on individual skids and performing work

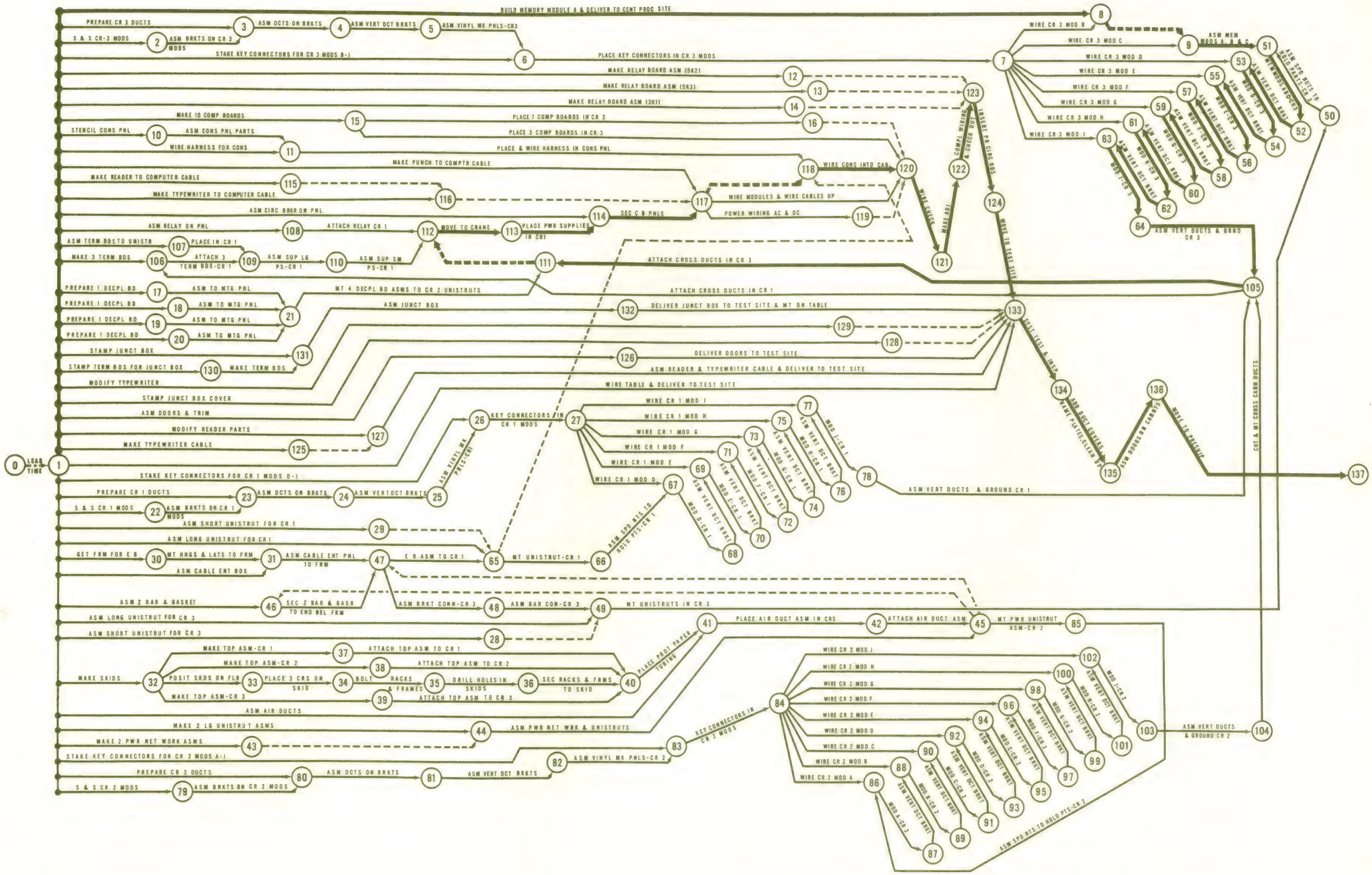


Figure 7. Arrow Diagram of an Electronic Equipment Manufacturing Project. Durations and Deliveries are not shown. The Critical Path is indicated by a heavy line.

on each of them separately. After insertion of modules, the three racks could be mechanically and electrically connected. As it turned out, this suggestion confirmed the recommendations of manufacturing engineering. Engineering had already started a technical feasibility study of introducing cables and connectors between adjacent cabinets.

It should be noted that the arrow diagram of Fig. 7 was an after-the-fact study of the inter-relationship of activities in the production of the central processor and does not include times nor restraints. It was done in an attempt to show the feasibility of manufacturing planning by the Critical Path Method and was in this respect successful, particularly so because the suggestions independently derived from a study of the arrow diagram completely coincided with the observations made by manufacturing personnel *after* production had started.

As the program now developed for the GE 225 becomes generally available, considerably expanded use of CPM is expected for planning, scheduling, and control of projects ranging from engineering development to manufacturing and marketing in the Computer Department.

EXTENSIONS AND FUTURE POSSIBILITIES

The Critical Path Method and PERT are in their infancy. Likened to the development of the automobile, we have here a "Model T" management tool -- simple, yet far advanced compared with the horse and buggy. As the work presently being carried out by many organizations in areas of implementation, application, and extension to these and similar methods becomes known, there is little doubt that astonishing results will be reported and even more sophisticated tools made available for project management and the individual workers.

Some of the concepts the future will bring into focus include an extension of the Critical Path Method into areas of schedule evaluation and review, and of PERT into inclusion of dollar resources.

A development presently underway attempts to formulate an optimizing *Resource Planning and Facility Levelling* scheme for inclusion in a computerized solution to CPM based data.

Since present methods consider only one project at a time, *Inter-Project Scheduling* is of interest and future work on CPM and PERT must extend these methods to allow for planning, scheduling, and control of many projects sharing similar facilities. In terms of the central processor example of Fig. 7, production of many models of central processors sharing the same factory floor space, the same manufacturing equipment, and personnel represents one kind of inter-project scheduling.

A number of interesting relationships between CPM and other modern management tools have occurred and may point to other areas of future work. One such relationship is that with simulation already indicated in connection with the discussion of Fig. 7. Indeed, a number of similar elements exist in simulation and in CPM. However, the two methods should not be thought of as rivals but rather as two different tools which may well complement each other. It is a difficult task to simulate a large, diversified operation. It is, however, a reasonably simple task to prepare an arrow diagram and to obtain the necessary input for computation of the critical path. CPM computations could then be expected to point to those parts of the over all operation which warrant closer study by methods such as simulation. In this sense, simulation and CPM may go hand in hand as important management tools. It is also important to recognize that CPM is *not* a simulation technique.

Another relationship seems to be indicated with the concept of decision structure tables (see 24). In the arrow diagram, the precedence relationship between activities in a project is structured. In the structure tables the sequence of decisions and the precedence relationship between decisions in a design procedure is structured. These two concepts could conceivably be unified, bringing the mathematical formulation and computational algorithms of CPM to benefit decision structure tables and vice versa.

In a "blue sky" sense one could conceive of on-line applications of the Critical Path Method using data collection devices at work stations continually or periodically feeding data to a computer programmed for acceptance of such input, conversion to input necessary for CPM calculations, updating on an on-line basis of the critical path diagram, earliest, latest, and scheduled completion time calculations, and identification of new critical activities. By an immediate computation of alternative schedules, the computer could supply output which management, or the computer, would use to decide to increase or decrease work performance speed so as to keep an over all even flow of work output consistent with established production criteria.

Many such applications come to mind as one gets more familiar with the method. Some of them may seem rather "wild" but then, on the other hand, the method is still young and our knowledge of application is likewise in the "Model T" stage.

CONCLUSIONS

The Critical Path Method has been presented in some detail. Emphasis has not been placed on calculational details, the mathematical structure, nor computational algorithms. We have, however, attempted to show the application of this method to the management of projects. The Critical Path Method represents a basic tool available to all levels of management from the individual professional contributor to "top management". It is a method which will help place the decision-making process at those levels of management which are closest to the point at which work is being performed.

This method, which includes elements of timeliness, selection, and evaluation, will help in the planning of increasingly complex, projectized businesses. *CPM is a tool which provides for true management by exception.*

The computer is used extensively. It is used to take the guesswork out of decision-making and produces alternatives in terms of the two most precious resources of business -- time and dollars. CPM will help to effect stimulative thinking and to produce new ideas for effective accomplishment of established objectives. The tool is of a cross-function nature and will aid in the integration of all the functions of the business involved in any specific project and in interrelating the work of engineering, manufacturing, marketing, and finance.

As the Critical Path Method becomes widely accepted and applied, and as the extensions worked on today become tomorrow's realities, we are able to visualize a process through which the high-speed computer "can become the nerve-center of a complete business operation" (25) with results including better values to the customer as well as higher earnings for the enterprise.

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Usually a technical paper reports solely the author's work. This article does not fall into this category. It is considered proper in this case to thank my many General Electric Company colleagues who, through enthusiasm and constructive discussion, have participated in this CPM effort. In particular, thanks are due Messrs. C.T. Clingen, W.L. Hainlin, and T.M. Lahey, members of the CPM project team. Also I wish to thank Mr. J.E. Kelley, Jr. and Dr. R.L. Martino of Mauchly Associates for their contributions based on their experience with CPM since its conception. Thanks are finally due Mrs. Trudy Smith. and Mr. Bruce Skaggs for their suggestions and help in composition and their review of this paper.

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